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Review

Current strategies and perspectives in detection and control of basal stem rot of oil palm

Yasmeen Siddiqui [a,*], Arthy Surendran [b,*], R. Russell M. Paterson [c,d], Asgar Ali [e,*], Khairulmazmi Ahmad [a,c,*]

[a] Sustainable Agronomy and Crop Protection, Institute of Plantation Studies, University Putra Malaysia, 43400 Serdang, Selangor, Malaysia
[b] School of Biological Sciences, Universiti Sains Malaysia, 11800 Minden, Penang, Malaysia
[c] Department of Plant Protection, Faculty of Agriculture, University Putra Malaysia, 43400 Serdang, Selangor, Malaysia
[d] Centre of Biological Engineering, Gualtar Campus, University of Minho, Braga, Portugal
[e] Centre of Excellence for Postharvest Biotechnology (CEPB), School of Biosciences, The University of Nottingham Malaysia Campus, JalanBroga, 43500 Semenyih, Selangor D.E, Malaysia

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ABSTRACT

The rapid expansion of oil palm (OP) has led to its emergence as a commodity of strategic global importance. Palm oil is used extensively in food and as a precursor for biodiesel. The oil generates export earnings and bolsters the economy of many countries, particularly Indonesia and Malaysia. However, oil palms are prone to basal stem rot (BSR) caused by *Ganoderma boninense* which is the most threatening disease of OP. The current control measures for BSR management including cultural practices, mechanical and chemical treatment have not proved satisfactory. Alternative control measures to overcome the *G. boninense* problem are focused on the use of biological control agents and many potential bioagents were identified with little proven practical application. Planting OP varieties resistant to *G. boninense* could provide the ideal long-term solution to basal stem rot. The total resistance of palms to *G. boninense* has not yet been reported, and few examples of partial resistances have been observed. Importantly, basidiospores are now recognized as the method by which the disease is spread, and control methods require to be revaluated because of this phenomenon. Many methods developed to prevent the spread of the disease effectively are only tested at nursery levels and are only reported in national journals inhibiting the development of useful techniques globally. The initial procedures employed by the fungus to infect the OP require consideration in terms of the physiology of the growth of the fungus and its possible control. This review assesses critically the progress that has been made in BSR development and management in OP.
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Contents

1. Introduction . . . 2841
2. The pathogen, occurrence and distribution . . . 2841
3. Epidemiology and symptoms . . . 2841
4. Detection of basal stem rot disease . . . 2843
 4.1. Detection methods . . . 2843
  4.1.1. Molecular and biochemical . . . 2843
  4.1.2. Remote sensing . . . 2844

* Corresponding authors.
E-mail addresses: yasmeen@upm.edu.my (Y. Siddiqui), arthy.surendran@gmail.com (A. Surendran), asgar.ali@nottingham.edu.my (A. Ali), khairulmazmi@upm.edu.my (K. Ahmad).

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5. Management of BSR disease . . . 2844
5.1. Physical control . . . 2844
5.2. Chemical control . . . 2844
5.3. Biocontrol. . . . 2845
5.4. Biodegradation of OP debris for disease control . . . 2846
5.5. Resistant planting materials . . . 2846
6. Conclusion . . . 2846
Declaration of Competing Interest . . . 2846
Acknowledgement . . . 2847
References . . . 2847

1. Introduction

Oil palm (*Elaeis guineensis* Jacq.) is an important crop cultivated widely in Southeast Asia, Africa and Latin Americ (Liew et al., 2015). The palm produces 3–8 times more oil than any other oil crop such as canola, sunflower, soy and rapeseed (Barcelos et al., 2015). High output, easy establishment, and low cost of production make the crop very profitable (Dislich et al., 2017). Indeed, palm oil is a huge global industry valued at USD 65.73 billion in 2015 and is expected to reach USD 92.84 billion in 2021, of which 85% is produced by Indonesia and Malaysia (Bentivoglio et al., 2018; Fathana, 2018; USDA, 2012). As palm oil is the lowest priced oil (USDA, 2018), it is expected to continuously attract demand globally. Thus, the sustainability of the oil palm industry is critical to ensure continuous production.

World palm oil production yields in Malaysia and Indonesia have increased, especially between 1998 and 2008 with yield increases of 4% annually. However, an unexpected decline in growth pattern has been observed since 2009 (USDA, 2012), indicating that significant events have occurred to cause this decline. One of the factors is OP is prone to attack by various diseases (Corley and Tinker, 2015) and fruit bunch yield reduction caused by pest and diseases may contribute up to a yield loss ~50 to 80% (Woittiez et al., 2017). Basal stem rot (BSR) caused by the fungus *Ganoderma boninense,* is of major concern to sustainability in Malaysia and Indonesia and it is predicted that more than 60 million mature OP could be infected in Malaysia (Midot et al., 2019; Olaniyi and Szulczyk, 2020).

Fruit bunch yield reduction of between 0.04 and 4.34 t ha^{-1} from 10 to 22 year of planting has been reported and 400 thousand hectares could be affected by BSR (Roslan and Idris, 2012) reducing yields by ca. 50–80% (Corley and Tinker, 2015). The malady can result in stand losses between 50 and 85% over the 25-year economic life of OP in the field when replanted after coconut (Ariffin et al., 2000), A 1% disease incidence caused an annual loss of 38 M US$ in Indonesia using 1996 prices (Darmono, 2000) and BSR caused losses of 50–350 M US$ per annum (Ommelna et al., 2012). Whereas, economic losses estimated at $365 million per annum in Malaysia (Seman, 2018). Peat soil was once assumed to be non-conducive for BSR disease development due to their acidic nature, however, disease incidence in oil palm planted on peat have been reported (Azahar et al., 2011; Pratibhan et al., 2016; (Rashid et al., 2014). Therefore, growing OP in peat soils is no longer considered a barrier to the disease (Midot et al., 2019) indicating that a significant change in climatic conditions has occurred. Further, climate change will have a devastating effect if not ameliorated.

The current review summarizes the stratagems to (a) detect and manage the disease, (b) highlight where there are inadequacies and (c) recommend optimal methods. Considerable effort has been expended to include information based on a global perspective.

2. The pathogen, occurrence and distribution

Basal stem rot was first described in the Republic of Congo (Wakefield, 1920) and *G. lucidum* was considered erroneously as an agent of BSR (Thompson, 1931). *Ganoderma* is a genus of polypore fungi. It belongs to phylum Basidiomycota, class Agaricomycetes, order Polyporales and family Ganodermataceae (Du et al., 2019). In general, they are recognised by ellipsoid to ovoid, double-walled and truncate basidiospores (Audet 2010 & Karsten 1881). Turner (1981) listed 15 species of *Ganoderma* associated with BSR in Malaysia and Indonesia, including *G. boninense*. The most prevalent names of taxa infecting OP were *G. boninense*, *G. miniatocinctum*, *G. chalceum*, *G. tornatum*, *G. zonatum* and *G. xylonoides* (Steyaert, 1980) and *G. boninense* is considered the most aggressive representative. Many species of *Ganoderma* are white rot, wood-decaying fungi with a worldwide distribution ((Zhou et al., 2015). Isolations of basidiomycetes similar to *G. boninense* have been made in tropical countries such as Indonesia, Malaysia, Nigeria, Colombia, Ecuador, Ghana, Papua New Guinea and Cameroon, although it is probable that some of the fungi were not this species.

Sumatra, Indonesia has an average OP infection rate of ca. 45% (Paterson, 2019a) and Peninsular Malaysia is at ca. 30% with Sarawak and Sabah being lower (Paterson, 2019b). BSR of OP in Thailand remains low: Pornsuriya et al. (2013) indicated that levels were 1.53%, although the disease was experienced widely in southern plantations. Papua New Guinea has an important palm oil industry (Corley and Tinker, 2015) and the level of BSR is not as high as in some other areas of SE Asia, although 50% has been recorded (Pilotti, 2005; Pilotti et al., 2018). The Philippines has an OP industry at a lower level than that of Thailand (Corley and Tinker, 2015) since distances between plantations will be high and BSR will be low as the plantations are far apart and have only been established recently (Woods, 2015). Equally, there are no reports of infection by BSR as determined by Google and Scopus searches of the literature. BSR is also considered a potential threat to Africa (Fonguimgo et al., 2015; Pilotti, 2005; Rees et al., 2009; Tengoua and Bakoume, 2005) with lower incidence in Latin America (Breton et al., 2009).

3. Epidemiology and symptoms

Infection can occur at any point in the life cycle of OP (Rees et al., 2012). Young palms usually die within 6–24 months after the first symptoms, whereas mature palms may take another 2–3 years. A schematic representation of BSR disease progression and respective symptoms that appear at each stage of the infection is illustrated in Fig. 1.

The first symptoms of infection are similar to drought conditions and the use of ergosterol analysis (see later) may be useful to determine if a fungus was involved. Fully elongated but unopened spears are seen in the center of the crown (Corley and

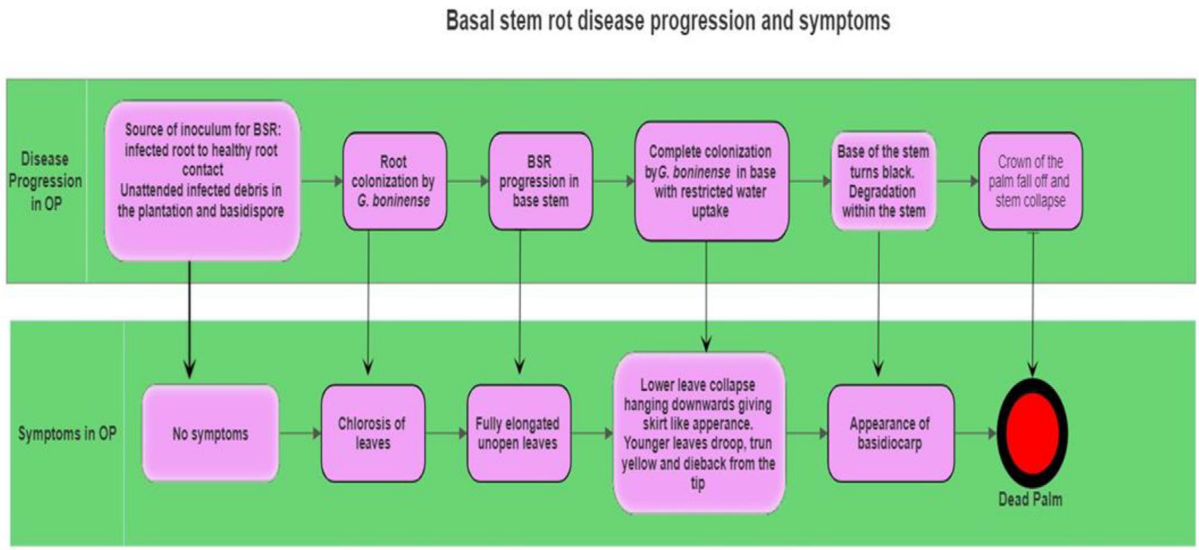

Fig. 1. Schematic representation of basal stem rot disease progression and the respective symptom in oil palm trees.

Tinker, 2015) which indicates the stem or root system is extensively damaged, thereby restricting water uptake, but this is not diagnostic for BSR. The lower leaves collapse in old palms hanging downwards vertically from the point of attachment to the trunk (Fig. 2 A). Drooping of younger leaves follows, which turn pale olive green or yellow and die back from the tip. The base of the stem blackens and gum may exude and then basidiomata appear (Fig. 2 B). The crown of the palm may then fall off or the trunk collapses. The peripheral tissues are hard and unaffected by rot, with the black fibers in this zone being normal: The stem tissue is yellow and disintegrates readily within the stem and become hollow at the base (Fig. 2 C) and mycelium can be found extended through the tissues.

Roots are also infected with the cortex being brown and decaying with the stele being black.

The fungus colonizes the cortex, endodermis, pericycle, xylem, phloem and pith of the palm (Rees et al., 2009) and it may be observed as a whitish skin-like layer on the inner surface of the exodermis in older roots. Roots are often found completely dead and colonized by many saprophytic micro-organisms, as they are often infected before foliar or stem lesion symptoms are observed. Basidiomata frequently appear along the entire trunk once the

Fig. 2. A) BSR infected matured oil palm tree at the final stage of infection. The lower leaves collapse in old palms hanging downwards vertically from the point of attachment to the trunk that makes a skirt-like appearance (arrow). B) Distinctive basidiocarps at the base of the oil palm trees (arrows); C) Disintegrated stem base eventually turning hollow within at advance stages of infection (images are from a personal collection of Dr Yuvarani Naidu, Malaysian Palm Oil Board).

palm dies, indicative of a more rapid saprophytic colonization. It is only assumed that the undifferentiated fungus in these studies was *G. boninense* as formal identifications are seldom carried out.

The infected OP debris left in the plantation is an important source of inoculum (Flood et al., 2000; Rees et al., 2007). The early infection requires biotrophic phase followed by aggressive necrotrophic phase where the pathogen begins to secrete extensive cell wall degrading enzymes to intrude further and decay plant tissues (Bahari et al., 2018; Cooper, 2011). The possible third phase is also suggested when production of pseudosclerotia or melanised mycelium in the host tissues and the roots' surface is evident. Spread by basidiospores is common in OP plantations as reported for Papa New Guinea (Pilotti et al., 2018) and presumably elsewhere (Sanderson et al., 2000).

4. Detection of basal stem rot disease

In general, the strategies for the early detection of BSR and its control are inaccurate or ineffective (Chong et al., 2017; Fowotade et al., 2019) to date. Many reports are published with significant amounts of data on laboratory or nursery level having low scientific veracity, which has hindered progress. Early detection is still difficult as affected oil palm can appear symptomless in the early infection stage and this is the major hurdle in BSR disease management. The emergence of basidiomata on the palm trunk base has been the only diagnostic method (Lelong et al., 2010), but this occurs too late in the disease cycle to save the palm. The first diagnostic techniques involved isolating *Ganoderma* using *Ganoderma* selective medium (Lim and Fong, 2005), which is time-consuming and relies on taxonomic skills which may not be available, whilst recognizing the general difficulty with *Ganoderma* taxonomy. The dichotomous scheme in Zhou et al. (2015) will be very useful in standardizing future identification.

4.1. Detection methods

4.1.1. Molecular and biochemical

PCR techniques have been recommended for early detection (Mandal et al., 2014). A combination of (a) bulk screening of samples by ELISA, (b) PCR to confirm the accuracy of results and (c) isolation and identification of *G. boninense* (Utomo and Niepold, 2000) was accurate, although inherently time-consuming and complicated. Besides, ELISA suffers from cross-reactivity (Idris and Rafidah, 2008). PCR is unsuitable for large-scale field monitoring since they are complicated, time-consuming and have precision limitations. Hushiarian et al. (2013) reviewed the molecular detection of *Ganoderma* and concluded that they are vulnerable to contamination. Also, an internal amplification control is a basic requirement to avoid false-negative results from inhibitors (Paterson et al., 2008). A comparison of conventional PCR and loop-mediated isothermal amplification (LAMP) has been utilized. It was claimed that LAMP was more sensitive than PCR to distinguish between pathogenic *G. boninense* and non-pathogenic *G. tornatum*: other actinomycete bacteria and basidiomycete fungi could also be separated (Madihah et al., 2018). The negative results for *G. tornatum* may have been from enzyme inhibition rather than a lack of a specific gene and hence may be a false negative: It is unclear whether LAMP in general, can detect false-negative results, whereas internal amplification controls can be employed with PCR (Paterson et al., 2015). DNA-based nano-sensors (Dutse et al., 2013), DNA microarrays and LAMP need further verification as the issue of DNA extraction and purification remain a challenge and field studies are required to determine their utility.

As'wad et al. (2011) compared ergosterol concentration in healthy and decayed OP seedlings and mature palms as a biomarker for early detection of BSR. Muniroh et al. (2014) described a more rapid and efficient ergosterol method which enables rapid analysis of field samples on-site by TLC. Ergosterol quantification is a presumptive diagnostic method for detection of *G. boninense* infection in OP and could be employed, for example, when the initial symptoms of the disease are observed to determine whether a fungus or drought is involved. This work is interesting although field trials are required.

Zainol et al. (2019) employed a headspace solid-phase microextraction (HS-SPME) technique integrated with gas chromatography-mass spectrometry (GC–MS) to investigate the volatile organic compounds (VOCs) secreted from *G. boninense* cultures and infected OP wood. Eight-carbon atoms aliphatic compounds such as 1-octen-3-ol, 3-octanone, 1-octanol and (E)-2-octenal, were roughly identified as the amplest components in the *Ganoderma* samples, while furfural and hexanal were the important constituents discovered in the OP wood samples. It was suggested that the novel method tested could be used to detect *Ganoderma* disease and, more generally, for chemoecological studies. Fowotade et al. (2019) have utilized the low-cost electroanalytical assay to detect of *G. boninense* in infected OPs. The paper presented more on the analytical characterization of the developed electrode rather than the detection of *G. boninense*. Consequently, a meaningful assessment cannot be given by the current authors.

There is a paucity of information concerning low molecular weight metabolites from *G. boninense* especially those that may be involved in pathogenicity. A chemotaxonomic study of the secondary metabolites produced by *G. boninense* is required. Nusaibah et al. (2016) analyzed the metabolites in the infected OP but did not consider those produced by *G. boninense* as a priority. Methods that assess the amount of growth within the plant may be useful and in particular, the assessment of ergosterol could help to standardize the procedures and make them objective (Muniroh et al., 2014). Much more work is required on the secondary metabolites that *G. boninense* produces.

Changes in protein profiles during infection of OP may be useful in the early detection of disease. A consistent and significant change in the abundance of root proteins after infection with *G. boninense* was recorded (Al-Obaidi et al., 2014). Enolase, fructokinase and ATP synthase were downregulated whereas, cysteine synthase, malate dehydrogenase was upregulated. Tan et al. (2013) reported gene expression profiles of 11 putative defense-related proteins from OP roots and leaves in response to inoculation with *G. boninense*. Two candidate genes (EgEMLP1 and EgMT) with different profiles in *Ganoderma*-treated leaves compared to that of *Trichoderma*-treated seedlings and untreated seedlings were identified. The proteins may be considered as biomarkers for the selection of resistant OP progenies. However, the work investigates genes in inoculated OP carried out using the same-days-post-inoculation method rather than, for example, degree of infection. Different amounts of infection may occur with the same-period-after-inoculation method leading to spurious results.

Transcript profiles of eleven putative defense-related cDNAs in the roots of OP, inoculated with *Trichoderma harzianum* and mycorrhizae at different times were studied and differences observed (Tan et al., 2015). This study provides an insight of these defense-related genes, and their roles as potential agents to boost the plant defense system. Yeoh et al. (2012) sequenced genes and determined expression of exo- and *endo*-glucanases in OP during fungal infection. The gene expression of a putative glucan exohydrolase in the root of OP seedlings was increased by *T. harzianum* but suppressed by *G. boninense* which may explain pathogenicity of *G. boninense*. Kwan et al. (2015) investigated nitrogen oxide (NO) expression which is associated with fungal infection. The induced expression of the gene EgNOA1 in *Ganoderma*-treated root tissues implies that it might be involved in plant defense responses against pathogen infection. A statistical analysis of gene expression was not carried out as recommended in more recent papers, and there was no control of a non-pathogenic fungus. Similarly, Tee et al. (2013) examined the transcriptome of OP seedling roots after *G. boninense* infection, but, again, a statistical analysis of upregulated or downregulated genes was not done. Hence the results are difficult to interpret. Yeoh et al. (2013) have a somewhat similar approach for chitinase enzymes and generally, a similar critique can be made as described further below.

In the papers on gene expression, a gene was considered to be differentially expressed if the abundance of transcripts increased 2-fold or decreased 50% compared to that of controls. The cut-off value of 2-fold change was used to avoid a high false discovery rate by statistical analysis alone, although the use of such cut off values is arbitrary and this technique has been superseded by more realistic methods. More recent authors used a combination of fold change and significance testing. A t-tests relative to a threshold (TREAT) method is perhaps the best approach (McCarthy and Smyth, 2009). Assessing the amount of infection may also be problematic as it is subjective, and infection symptoms may not show.

4.1.2. Remote sensing

Remote sensing (RS) techniques have been employed for BSR detection and quantification (Khosrokhani et al., 2018), although the methods are time-consuming. Shafri et al. (2011) reported that early detection of BSR was challenging because separating the healthy from the mildly infected samples was difficult, however, spectrophotometric vegetation indices (VIs) demonstrated the ability to distinguish between healthy and diseased OPs (Shafri et al., 2012).

A recent study using terrestrial laser scanner (TLS) remote sensing to detect BSR based on phenotypic features of infected and healthy oil palm reported average accuracy of 80% for severity level classification and 86.67% accuracy for healthy-unhealthy classification (Husin et al., 2020). The data collected was based on scanning single palm at a time which will not be feasible for industrial plantations and is time-consuming. Liaghat et al. (2014a, 2014b) classified the spectra of *Ganoderma*-infected OP leaves with an overall accuracy rate of 97% compared to healthy samples and were able to detect mildly-infected trees. It is possible that changes to carbohydrates, on which the method is based, could be from other factors apart from *Ganoderma* infection. The PCR confirmatory method used was not described properly and so it is impossible to determine if the results were accurate. Moreover, remote sensing is expensive and inappropriate for small farms. Healthy and BSR infected trees were detected early by using electrical resistance (Nurnadiah et al., 2014), vital for sustainable BSR management, although a practical method for the industry is unavailable. Hence, none of these methods are currently used routinely in plantations.

5. Management of BSR disease

Despite continuous research in combating the problem, the resolution remains stagnant. The current control strategies for BSR include physical, chemical and biological procedures. These methods are intended to (a) curtail the incidence of BSR after replanting and (b) increase the productive life of the infected OP. Surprisingly, the extent to which they are effective remains unknown.

5.1. Physical control

Sanitation involves elimination measures such as clean clearing and windrowing intending to minimize the spread of the inoculum. Infected palms can be chipped, pulverized and stacked in windrows between planting to promote natural decomposition, however, the procedures are expensive. Windrows may not prevent fungal pathogens survival which may infect healthy palm. Minimizing wounds to OP is an obvious method to avoid spread. The open burning technique was used but is banned in Malaysia under the Environmental Quality Act (EQA, 1974). The Indonesian government has issued numerous laws on land fires, especially after the fires in 1997–98 (Nurhidayah, 2013; Tan, 1999). However, regulatory frameworks suffer from weak enforcement. Also, exemptions allow open burning, although an amendment placed a complete ban on burning on any peat soils. The recent fires and haze in 2019 indicate that the issue remains problematic. The disease may be reduced by clearing OP before they reach the greatest susceptibility (Rees et al., 2009). As reported, removal of *Ganoderma* inoculum sources during replanting contributes to lower BSR incidence on oil palm in the first 9 years after planting whereas the incidence of BSR was maintained under 5% (Priwiratama et al., 2020). Digging trenches around infected palms (Wakefield, 1920) may have some value but requires scientific testing although disease spread by basidiospore dispersal would render the method useless (Pilotti et al., 2018).

Basidia prevention and removal may be useful as basidiospores are now recognized as the primary source of infection (Pilotti et al., 2018; Sanderson et al., 2000). Infected palms, trunk bases and root rings are required to be removed from the plantations. Removing basidiomata from diseased palms and painting them with carbolineum (fungicidal paste) (Turner, 1981) may be effective, although modern studies are required. Controlling BSR employing surgery of the diseased part of the outer stem has been proposed (Turner, 1981). A protectant chemical (coal tar or Thiram) was used to treat the open surfaces preventing further decay. Paints or fungicide as dressing can be a potential control. The efficacy of this method requires study urgently (Ariffin et al., 2000) and was more successful on younger palms than those older than 12 years. Soil mounding around the base of mature diseased palms can delay the development of BSR (Turner, 1981). Surgery-mounding of Ganoderma-infected palms can prolong the lifetime of the infected palms for 2 to 3 years (Priwiratama et al., 2020). However, these procedures require assessment in a rigorous scientific manner in field conditions to validate the method as a potential BSR management technique.

5.2. Chemical control

The use of fungicides requires careful consideration and results need reporting from field evaluation. This method, in combination with soil mounding, appears to be effective treatments, and the cost/benefits require reassessment. Pressurized trunk injection using hexaconazole may be useful (Mohammed et al., 2014). Melanised mycelium, basidiospores and pseudosclerotia are resistant to fungicides and may explain why they are not generally effective (Susanto et al., 2005) additionally, the defense mechanisms in plants may be inhibited by the fungicides (Oostendrop et al. 2001).

Studies employing low molecular weight phenolic compounds have been undertaken (Surendran et al., 2017). It was suggested that immunization of OP seedlings with benzoic and salicylic acid under heavy infection pressure reduced BSR development (Surendran et al., 2018a). Moreover, (Surendran et al., 2018b) and (Surendran et al., 2018c) emphasized inhibition of wood degrading enzymes from the fungus to prevent the disease. The environmental impact of using phenolic compounds in the field needs consideration as they are often toxic. But these are interesting initial investigations and fieldwork is required.

Mineral fertilizers play an important role in overall plant health. Sariah and Zakaria (2000a,b) demonstrated calcium nitrate in combination with the biological control agent (BCA), *Trichoderma* sp., suppressed disease. Rahamah Bivi et al. (2014) demonstrated impressive results *in vitro*: Calcium chloride + copper-EDTA + salicylic acid (SA) caused a significant decrease in disease symptoms. Continuous supplementation of calcium/copper/SA may be key to enhancing disease resistance in OP (Bivi et al., 2016) and higher lignin content was also apparent, indicating how resistance to infection could occur. EDTA is a potent inhibitor of ligninolytic enzymes of *G. boninense* (Siddiqui et al., 2019). This work requires urgent development. Silicon has beneficial effects on growth, yield and disease resistance in various plants (Wang et al., 2017). Najihah and co-workers (2015) elucidated that silicon oxide, potassium silicate, calcium silicate, sodium silicate, and sodium *meta*-silicate reduced the BSR severity in OP seedling. The accumulation of silica in host cell walls may have altered the ultrastructure of the roots and shoots hence deterring the pathogen from infection in an encouraging approach.

5.3. Biocontrol

A great deal of research has been undertaken on biocontrol application (BCA) of *G. boninense* but with little proven practical application. BCA often suffer from a lack of effectiveness in the field due to susceptibility to hostile environmental conditions. Microbial populations from the oil-palm rhizospheres and on the sporophores may have the potential to control *G. boninense* (Susanto et al., 2005). A list of work carried out on BCA in at least at the nursery stage is provided in Table 1 and forms the basis to find effective treatments.

Tolerance to stress through enhance root or plant development, solubilization of inorganic nutrients making them available to palms and inducing resistance in host plants may assist control (Susanto et al., 2005). *Trichoderma koningii* was tested against *G. boninense* (Soepena et al. 2000), but no data are available on its effectiveness in the field. *T. harzianum* alone or in combination with mycorrhizal preparation, dried palm oil mill effluent and calcium nitrate were tested on OP seedlings in a nursery trial and had a significant effect (Sariah and Zakaria, 2000). A field trial indicated that treatment with *T. harzianum and G. viride* was superior to *Bacillus* sp in that the disease incidence was lower in a field treated with the agents than untreated fields (Susanto et al., 2005). Similarly, *Trichoderma* induced the production of fungal cell wall degrading enzymes, such as glucanases and chitinases (Naher et al., 2011), as a possible defense mechanism in the OP, and these enzymes may degrade the cell wall of the invading fungus hence controlling the disease as discussed for other plant pathogens in Latgé (2007). Arbuscular Mycorrhizal fungi (AMF) are associated with the roots of OP and it has been speculated that they may inhibit *G. boninense* (Sundram et al., 2015). In general, AMF competes with the plant pathogens for the nutrients and space and may induce the plant defense system by inducing siderophores as discussed in other plant-pathogen systems (Brundrett, 2002).

Endophytic microorganisms have received attention as methods to control plant diseases as they may assist in inhibiting disease (Kobayashi and Palumbo, 2000). The inhibitory effect of endophytic *Pseudomonas aeruginosa* from healthy OP roots against *G. boninense* was studied *in vitro* (Bivi et al., 2010). Esyanti et al, (2017) utilized four endophytic fungi; *T. harzianum*, *T. longibrachiatum*, *Lasiodiplodia venezuelensis* and a *Dothidiomycetes* sp. which were able to induce pathogen-related protein in the OP which partially explains control observed.

Actinomycetes isolated from empty fruit bunches of OPs showed an antagonistic effect against *G. boninense.* The isolates were identified as *Nocardiopsis* sp., *Streptomyces violaceorubidus* and *Streptomyces* sp., with percentages of inhibition of 91.4%, 86.4% and 69.1%, respectively (Ting et al., 2014). These organisms are useful as they are unlikely to cause disease of OP. However, field trials are required in all cases.

Biological control studies using basidiomycetes to prevent stump infections in forest trees have been conducted (Roy et al., 2003). No such study has been conducted on OP trunks infected with BSR. Twenty-five white-rot hymenomycetes were isolated from healthy OP (Naidu et al., 2015) and 8 showed antagonistic effects against *G. boninense.* Pathogenicity tests towards OP were conducted which indicated they were not pathogenic (Naidu et al., 2018). Yet, novel conditions under variation in climate may allow them to become pathogenic so great care would be required if used in plantations.

Theoretically, biocontrol is an advance compared to other approaches and numerous bio-fungicides are available in the market. The efficacy of the preparations in the field is a major concern and they have not cured BSR and the disease remains highly serious. This seems to be related to the abundance of Ganoderma inoculum in the field, particularly in Ganoderma-endemic areas.

Failures of BCA may result from interaction with non-target organisms, variation in the rhizosphere reducing efficacy, lack of ability to colonization in different types of soil, sensitivity to climate, problems competing with oversized populations of other microbes and the genetic diversity of the target pathogen (Meyer and Roberts, 2002). Their utilization as biofertilizers is challenging

Table 1
Potential biocontrol agents and their effect on basal stem rot management at least in the nursery with recommendations.

Classification	Bio-agent	Effect	Recommendation	Reference
Fungus	*Hendersonia* isolate (*GanoEF1*)	BSR incidence was reduced by 37.0% to 55.2% in six-month-old seedlings in nursery trial	Field trials required.	Nurrashyeda et al. (2018)
	Scytalidium parasiticum	Reduced disease severity and increased the vegetative growth of palms in nursery trial	Field trials required to confirm decreased pathogenicity and disease suppression.	Goh et al. (2016)
	Soil mounding + *T. harzianum*	Prolong the life of infected palm by 3 years after treatment in field evaluation	Inefficacy after 3 years was due to lost viability of bio-agent. More work on extending the shelf life is required. However, quite encouraging. It would be useful to know if both procedures required.	Priwiratama et al. (2014)
	Trichoderma sp.	Initial delay in infection in the field. Longer term was no difference from control.	Needs work to maintain efficacy	Hasan and Turner, (1998)
Bacteria	*Burkholderia* sp.	Seed treatment reduced the disease incidence observed up to three months nursery trial	Field trials are needed	Buana et al. (2014)
	Burkholderia cepacia, *Pseudomonas aeruginosa* and *Serratia marcescens*	Inhibit *G. boninense* between 42 and 76% in nursery trial	Field trials required	Sapak et al. (2008); Azadeh et al.(2010)

from (a) poor storage, (b) sensitivity to transport and handling and (c) complex application requirements (Vidhyasekaran et al., 1997). A potential further problem may be that some BCA fungi produce mycotoxins which could enter the environment or final product (i.e. palm oil). Only few BCA have been commercialized due to their unstable behaviour in the field. Available commercial products include Draz-M, a formulation of an arbuscular mycorrhiza that prolongs productivity of 25-year-old infected OPs and increased their oil yield by 42 and 68% (Sariah and Zakaria, 2000a,b). Similarly, *T. koningii* has been developed for use commercially in Sumatra as a preventative or curative treatment in the field (Soepena et al. 2000).

5.4. Biodegradation of OP debris for disease control

Once an OP has become diseased and actually fallen over, managing the infected debris is a major issue. The initial rate of degradation of OP is between 10 and 24 months (Paterson et al., 2000), this will allow *Ganoderma* to proliferate as the trunk is a good source of nutrients for the fungus.

A *Hydnum* sp. and *Pleurotus djamor* belonging to the basidiomycota grow well on the OP trunk, and outcompeted a *Ganoderma* sp *in vitro*. These fungi were considered as potential fungi to enhance wood degradation (Paterson et al., 2000). A study suggested that *Lenzites* and *Marasmius* species caused the highest rate of weight loss during wood degradation OP trunk, and ergosterol estimation was used to evaluate the ability to grow on OP trunk (Paterson et al. 2000). However, at least one species of *Marasmius* causes disease of OP and so care would be required if used in the field. These experiments were at a very early stage and further work is required.

White rot hymenomycetes were utilized to antagonize *Ganoderma* and increase the rate of OP debris degradation as mentioned above (Naidu et al., 2015). The results suggested a combination of white-rot fungal strains should be tested, owing to their substrate specificity and nature of degradation, to achieve a high rate of degradation (Naidu et al., 2017). Recently, Naidu et al. (2020) developed solid-state cultivated (SSC) ligno-hemicellulolytic biodegrader formulations of two indigenous white-rot hymenomycetes (*Trametes lactinea* and *Pycnoporus sanguineus*) utilizing agro-industrial wastes as substrates. These formulations not only contributed to significant mass loss of felled oil palm logs but also outcompeted *Ganoderma* sp when compared to control (data unpublished) whereby reducing the inoculum pressure. The use of non-pathogenic ligninolytic white-rot fungi as a natural means to eliminate the woody debris and to suppress *Ganoderma* represents an attractive alternative to chemical-based control. A complete understanding of lignocellulose degradation by white-rot fungi in OPs is required. Equally, a great deal of care is required that the white-rot fungus cannot attack the OP.

Strains of *Nocardiopsis*, *Streptomyces violaceorubidus* and *Streptomyces* spp. isolated from empty fruit bunches had enzymatic potential and antagonistic activity against *Ganoderma* (Ting et al., 2014). However, these are not white-rot fungi and will not degrade lignin as effectively as white-rot fungi. The authors concluded that indigenous actinomycetes can be used to accelerate the biodegradation of OP waste turning it to value-added compost which could be used to suppress BSR disease. However, the biosafety studies to both humans and environmental microbiome should be conducted in-depth before the application of these fungi in the field.

5.5. Resistant planting materials

To date, future management of BSR in oil palm is embarked with the use of genetic resistant materials (Breton et al., 2009; Rival and Jaligot, 2010). Progress in resistance breeding has been hampered for a long time by the lack of a plant resistance source and an efficient screening technique. A partial resistance source has been found in a Zaire × Cameroon cross derived from MPOB's semi-wild germplasm accessions, and its screening technique has been developed (Ariffin et al., 1995; Idris et al., 2004). The incorporation of this resistance into commercial varieties took a longer period, as it is derived from a semi-wild genotype requiring 5–6 generations (30–40 years) of backcross breeding to advanced breeding parents. Centre Internationale pour les Reserche et Develepement, (CIRAD), in collaboration with research laboratories in Indonesia worked on the development of Ganoderma resistant commercial varieties where partial genetic resistance was found by Durand-Gasselin et al. (2005), although the genes for *Ganoderma* resistance have not been investigated. Based on the findings it is expected to have a resistant variety by now which is not the case. Development of a fully resistant OP plant is problematic since defense-related genes have not been isolated.

The AVROS OP is the prevalent variety planted and is claimed to be more resistant to *G. boninense* in comparison to other commercial varieties (Chong et al., 2012). Recently, *Ganoderma* resistance loci were identified using an OP multi-parental population derived from ongoing breeding programs. Four *Ganoderma* resistance loci were recognized, two designated for controlling the manifestation of the initial *Ganoderma* symptoms, while the other two were for the death of palm trees (Tisné et al., 2017). The authors suggested that identification of quantitative resistant loci among an extended genetic diversity will allow testing their effects in various genetic backgrounds, which could enhance the transferability of results and the sustainability of the selected resistances. This study implemented an efficient and flexible QTL mapping approach and generated unique valuable information for the selection of oil palm varieties resistant to Ganoderma disease. This transgenic approach is potentially promising but unlikely to provide an immediately commercially acceptable solution.

6. Conclusion

The sustainability of OP cultivation is of immediate concern to farmers, processors and the countries involved in palm oil production due to threatening effects of BSR. *Ganoderma boninense* degrades the lignin component of the palm employing an arsenal of extracellular enzymes to enable the energy-rich cellulose to be utilized. When the cellulose is degraded the palm is vulnerable to collapse. Deeper knowledge is required to understand how *G. boninense* degrades OP lignocellulose. However, to commence the infection it is the more amenable carbohydrates that will allow initial infection and inhibition of the enzymes involved requires investigation. The crucial role of basidiospores in infection is accepted and should not be overlooked. The current control methods proved to be inefficient if not ineffective. There are too many reports limited to *in vitro* or nursery trials which may have dubious scientific merit. There are only a few investigations where control methods have been tested on a large scale in plantations and proven to control the disease beyond any doubt: These are likely to be the most suitable methods for general application. One might expect a preparation would be available from the promising findings, but this is not the case. We have entered a new paradigm where all methods require to be re-evaluated. Finally, there requires much greater focus in developing the leads (lab-scale research) into actual products that are proven to work consistently.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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